RIVER TRAINING VS. FLOOD RISK IN THE UPPER VISTULA BASIN, POLAND

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Abstract: This paper assesses the effect of river training in the 20th century on the evolution of flood risk in the middle and lower courses of certain Polish mountain and upland rivers, and in the lowland Carpathian foreland. The overall anthropogenic impact on the flood risk is a combination of two contradictory trends: (a) the shortening of the floodplain inundation time (between the levees) as a result of the deepening of the trained channel; and (b) the increasing height of the flood water and frequency of flood culminations, a result of the flood wave transformation. The author, in his flood risk analysis, regards the former trend as the more influential. The highest levels of all types of flood risks were found along the valley reaches with unembanked channels that displayed a tendency to reduce both their depth and gradient. This type of reach occurs immediately downstream of embanked reaches with a deepened channel. The author also addresses ways to mitigate flood risk levels, taking into account limitations stemming from local land development and legal conservation status.

Key words: flood risk, flood, upper Vistula basin, river training.

INTRODUCTION

Flood risk should be understood as the likelihood of economic losses being suffered within a floodplain as a result of flooding by overbank culminations of a moving flood wave. It depends on the duration of the overbank discharge and the vertical and horizontal extents of flooding within the embankments. Contemporary flood risk is modified by human activity, and its level is a combination of the hydrological effects of processes of long duration, such as drainage basin deforestation, agricultural expansion, urbanisation and river training. This activity modifies, not just the duration and extent of flooding, but also the pace of concentration and speed of flood wave movement.

One of the purposes of river training is to reduce the flood risk by accelerating the drainage of a submerged floodplain along a deliberately shortened channel. River training projects trigger processes of systematic deepening along the shortened and steepened reaches, and shallowing along reaches with a less steep gradient (Brookes 1990; Łajczak 1995a). This accelerates the flow velocity and, in embanked rivers, also increases the water level amplitude. Along the reaches with fast deepening channels the duration with an overbank water level may tend to reduce. However, an increased concentration of flood waves and increased water level amplitude in the upstream reach may increase the flood risk along those less steep reaches further downstream where the embanked cross-section volumes are low (Punzet 1991; Wyżga 1993; Łajczak 1995a). It is possible to control floods on trained rivers effectively by means of river dams (Punzet 1959, 1973). This is however impossible on rivers utilised for navigation, since this type of hydrotechnical structure is absent.

River training has been increasingly perceived as a controversial activity and sometimes also as a contradictory one that does not produce the expected reduction in flood risk (Kajak and Okruszko 1990; Andrews and Burgess 1991; Finlayson 1991; Angelstam and Arnold 1993; Łajczak 2006a, b). A heightened flood risk resulting from river training has only been noted over the last 20 years (e.g. Cooper *et al.* 1987; Howard 1992; Kajak 1993). This can be seen, in particular, along those reaches that are becoming shallower. A heightened ground water table in the valley, one of the effects of the channel shallowing downstream of the fast-deepening channel reaches (Żelazo 1993), further extends the duration and extent of excessive water content within the floodplain beyond the flood embankments.

STUDY OBJECTIVE AND MATERIALS

This paper looks at the change in the flood risk in the upper Vistula drainage basin, as a result of river training during the 20th century. The study focuses on three rivers running through mountains, foothills, uplands and lowland forelands (the Rivers Raba and Nida, and the foreland course of the Vistula). The paper is based on the literature, the author's own research in the upper Vistula and Nida Valleys, and on data supplied by the Institute of Meteorology and Water Management.

STUDY AREA

In Poland there are two areas in which summertime or early springtime floods predominate, and turn into catastrophic events every few years (Fig. 1). One covers the drainage basins of the mountain tributaries of the rivers Vistula and Odra and the foreland courses of those rivers, while the other spans the Vistula's and Odra's upland and lowland tributaries, including those located in foreland areas. Most of the upper Vistula river system features a predominance of summer rain floods, both annually and in the long-term. On the River Raba, a typical Western Carpathian watercourse, the flood risk is restricted to the summer season, while on the River Nida, the longest upland tributary of the upper Vistula, it is restricted to the early springtime, and less often the summertime. The foreland course of the upper Vistula has a hydrological regimen driven primarily by its mountain tributaries. Currently, the flood risk along this course of the river is limited to the summer months, but the early spring is also added, downstream of the River San confluence (Dynowska 1971; Ziemońska 1973; Punzet 1991).

About a century ago, the beginning of hydrological records (on water levels and discharges) coincided with the first active and passive measures mitigating flood risk in the Upper Vistula valley. The records can now be used to assess the evolution of flood-risk patterns, whether caused by natural or by human-induced processes.

The attempts at river training olong the course of the River Vistula that form the subject of this study started at the end of the 19th c. and lasted throughout the 20th. They changed the earlier trends in the channel

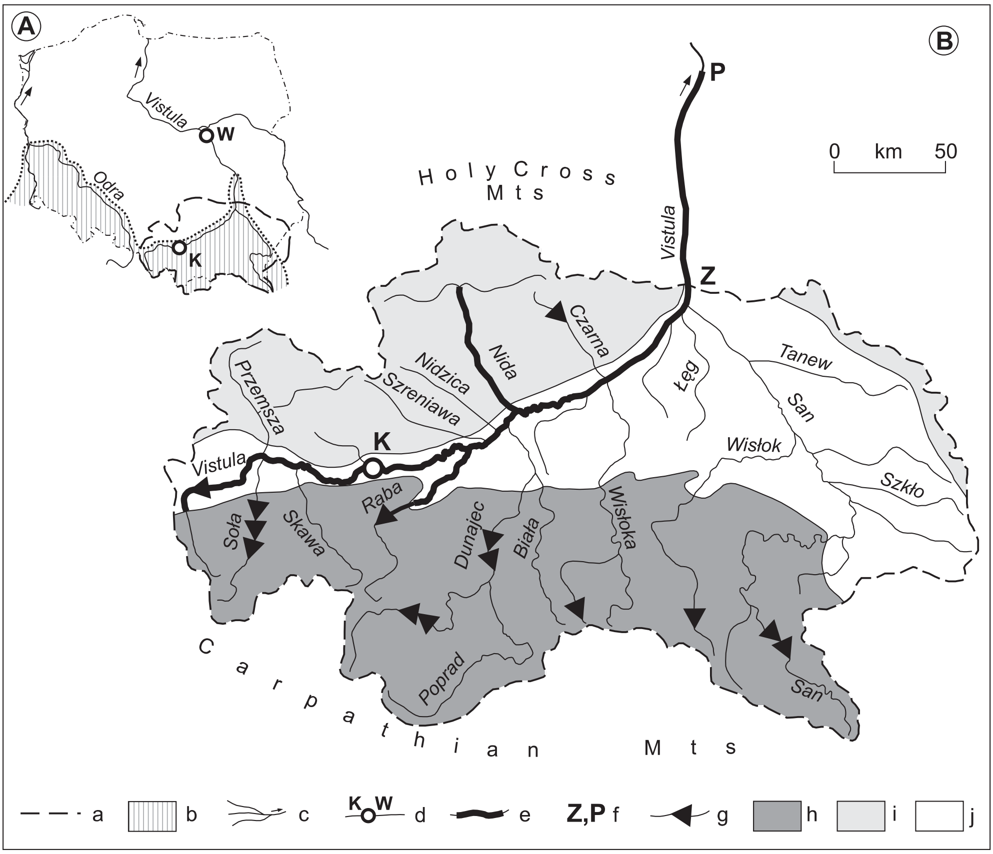

Figure 1. The upper Vistula drainage basin on the map of Poland (A).
River network against principal geomorphological units (B).
a) limit of the upper River Vistula drainage basin, b) area dominated by summer rain floods,
c) main rivers, d) Cracow (K) and Warsaw (W), e) river reaches (Vistula, Raba and Nida) analysed in the paper, f) water gauge at Zawichost (Z) and Puławy (P) measuring the outflow from the upper Vistula drainage basin, g) large dams. Principal geomorphological units in the basin: h) Carpathian Mts., i) Polish Uplands, j) Sub-Carpathian basins.

development of its tributaries, involving both shallowing and broadening. The morphology of the Carpathian river channels, which are crucial for the supply of water and bedload and suspended load to the Vistula, exhibit regional differences (Klimek 1979). The westernmost gravel-bedded tributaries down to and including the River Dunajec are more susceptible to change under the influence of river training than the eastern tributaries (the Wisłoka, Wisłok and San), which often feature bedrock channels along their mountain courses in the Beskidy Mountains. The erection of numerous rubble dams in the Carpathian Mts. reduced bedload transport along the upper courses of mountain rivers and streams, while river dams, the first of which was built in the 1930s, have been intercepting all of the bedload and most of the suspended material. As a result, the pace of shallowing downstream of the dams has been reduced. This has been further assisted by a reduction in the supply of bedload from the channel banks after their reinforcement with stone bands. From the flood-risk point of view, the greatest hydrological consequences have been engendered by the deepening and narrowing of the channels, a process started in the early 20th c. On the River Vistula and the lower courses of its mountain tributaries this process was mostly driven by channel shortening (Punzet 1981; Klimek 1987; Wyżga 1993; Łajczak 1995a; Wyżga and Lach 2002). Along the upper courses of the Carpathian rivers, this development trend is assisted by a growing afforestation of their drainage basins, since the mid 20th century, and by the trend for field tracks in the depopulated areas of the Beskid Niski and Western Bieszczady ranges to revegetate (Izmaiłow *et al.* 2003).

River training has also included flood embankments erected along the foreland course of the Vistula, along the lower courses of its Carpathian tributaries and also locally along their intra-mountain-basin courses, along the lowland tributaries and some of the upland tributaries (Hennig 1991). The insufficient embankment-to-embankment space that resulted has reduced the zone liable to flooding by a factor that is often larger than 10 (on the River Vistula). Subsequent effects included higher maximum water levels on the River Vistula, (up to twice as high along the Cracow reach), and a faster travelling flood wave (Soja and Mrozek 1990; Punzet 1991).

CHANGES IN FLOOD RISK DURING THE 20TH C.

CARPATHIAN RIVERS USING THE EXAMPLE OF THE MIDDLE AND LOWER RABA

The River Raba provides an example of a gravel-bedded Western Carpathian river draining the Beskidy Mts., the Carpathian Foothills and the lowland Carpathian foreland (Fig. 2). The newly constructed river training along the course of the river has led to a shorter, narrower and deeper channel. In the aftermath of the river training measures the channel deepened by more than three metres in its middle and lower course, a typical value recorded on the lower courses of other Carpathian tributaries of the River Vistula. The channel also increased in compactness through a lowering of the width to average depth ratio. This change resulted in an increased water flow velocity, particularly during flood events, and consequently in greater concentrations of flood waves and increased speeds of flood wave travel (Wyżga 1993). As a further consequence, the differences between the maximum flood water levels recorded during the same events on the lower course of the Raba and on the middle course of the river have been increasing since the second half of the 20th century. (Fig. 3). The faster flow in the deeper channel results in a higher bankfull discharge at the expense of overbank discharge. The narrow embankment-to-embankment space in the lower course of the river additionally forces maximum water levels to become ever higher, while shortening the duration of the flood wave event and increasing the flood wave velocity. Such a flood wave profile has a considerable impact on the flood situation along the River Vistula.

The Raba is one of those Carpathian rivers wherein the assessment of the impact of river training on the evolution of the flood risk is far from easy and straightforward. On the one hand, engineering has brought a reduction in flood risks along the trained reaches in terms of flood duration and area affected. Indeed, the flood wave travel times and the number of overbank discharge days have been reduced, and the floodplain inundation time is down dramatically. On the other hand, the greater flood wave speeds may, in certain situations, shorten the time local communities have to mount an

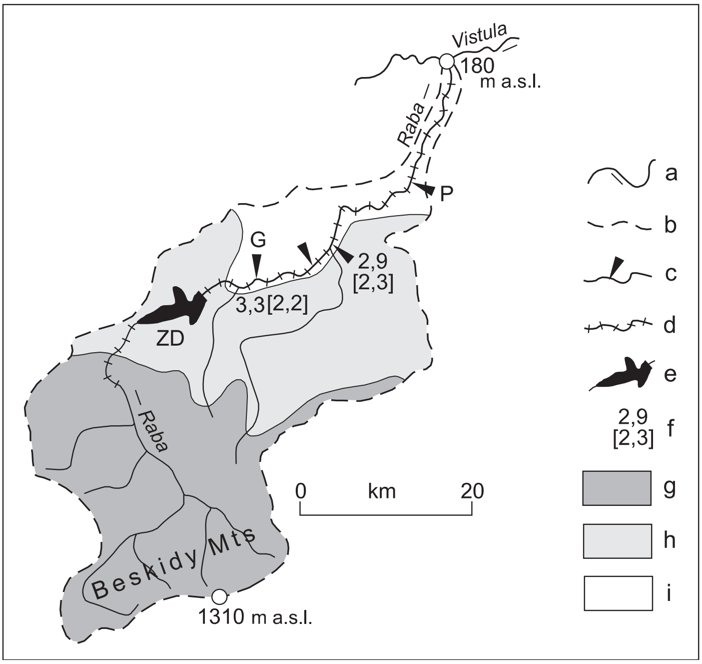

Figure 2. The River Raba drainage basin.
a) main rivers, b) limit of the drainage basin, c) selected water gauges in the middle and lower courses of the river, G- Gdów, P- Proszówki, d) partly or fully trained reach of the river, e) artificial lake Dobczyce (ZD), f) deepening [m] of the Raba channel at selected water gauges following river training in the 20th century, in parenthesis the value related to the second half of the 20th century (according to Wyżga 1993). Geomorphological units in the basin: g) Beskidy Mts., h) Carpathian Foothills, i) Sub-Carpathian basins.

adequate response, and therefore be considered to increase the flood risk. Additionally, river training has increased flood risks along the untrained reaches downstream, as reflected by the increasing maximum flood wave levels in the lower course during the largest events. This trend is observed despite a parallel trend to reduce the volume of the flood wave, as measured above the bankfull stage. A further flood risk improvement could be achieved via effective use of the Dobczyce Dam, especially in view of the mostly positive experience with dams as flood management instruments on other Carpathian tributaries of the Vistula (see: Punzet 1959, 1973, 1991).

UPPLAND RIVERS EXEMPLIFIED BY THE MIDDLE AND LOWER NIDA

The River Nida is an example of an upland river with a sandy channel and a low gradient in its middle and lower courses (0.2–0.5‰). Along this stretch, the river meanders with a meander coefficient that reaches 2.0 locally. Its floodplain is regularly submerged during springtime floods, and less often during summertime, and the water can stagnate for over three months. During the period 1950–1995, the middle course (between Brzegi and Pińczów) was shortened and partly equipped with flood embankments, and extensive wetlands were also drained within the floodplain, especially along a long anastomosing

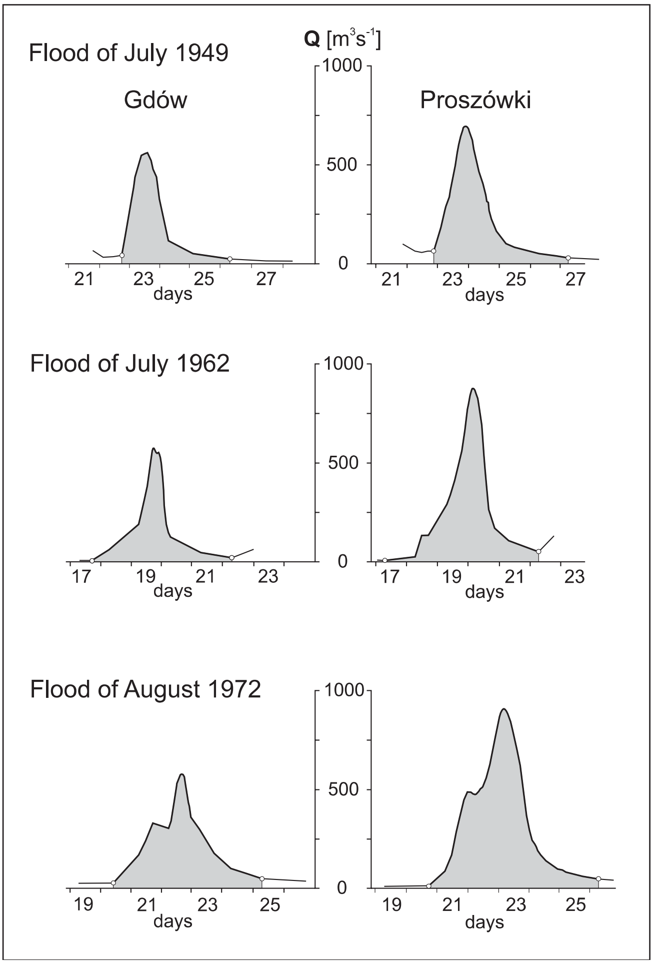

Figure 3. Hydrograph of selected flood waves in the middle and lower River Raba courses between Gdów and Proszówki.

reach near Umianowice (Łajczak 2006b). The lower course of the river (downstream from Pińczów) has remained untrained, with a natural channel and floodplain (Fig. 4). The river training has been aimed at accelerating the draining of flooded areas and the drying out of the floodplain. From the point of view of flood control, the result has been mixed.

The river has begun to deepen its shortened channel, as recorded by a water gauge at Brzegi (Fig. 5). Because of the slow transport of sand, the river has been observed to become shallower downstream around Pińczów, initially in the old channel but more recently (since 1970) also in the new, initially deep channel. This process varies in speed, and depends on the intensity of the upstream river training work. The zone subject to the shallowing process is moving, but has not yet reached the next water gauge at Wiślica. The slow downcutting trend along the mouth

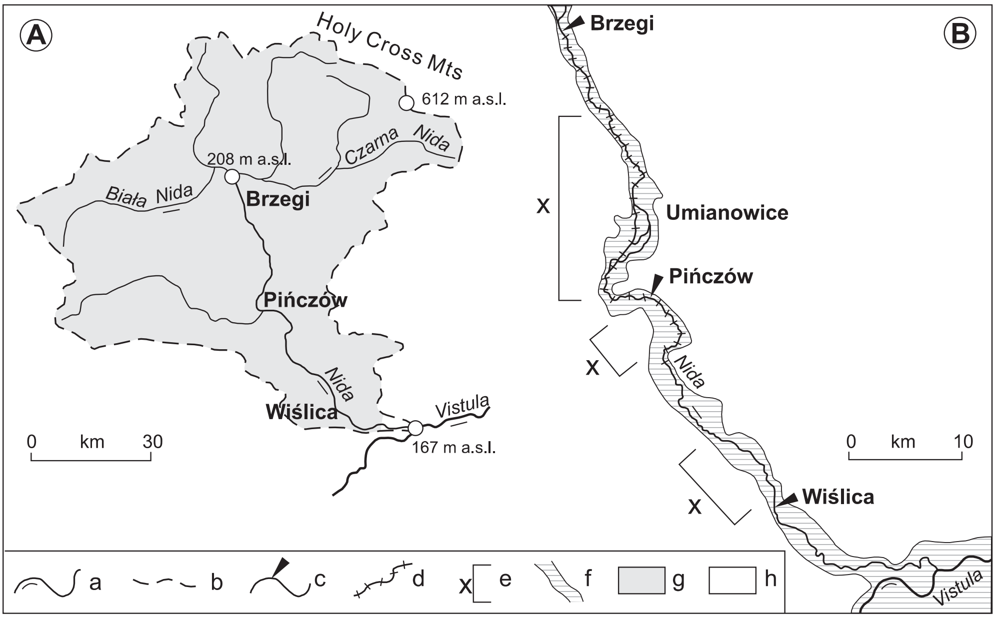

Figure 4. River Nida drainage basin (A) and middle and lower courses of the river (B).
a) main rivers, b) limit of the drainage basin, c) water gauges, d) partly trained river reach,
e) formerly anastomosing reaches of the river currently partly or fully trained, f) floodplain extent.
Geomorphological units in the basin: g) Polish Uplands, h) Sub-Carpathian basins.

reach of the Nida below Wiślica is a result of a similar trend on the Vistula since the beginning of its training in the late 19th century. On the deepened reach of the Nida, the bankfull discharge volume has been growing, as recorded by the water gauge at Brzegi. During the period 1939–1990, this produced a trend whereby the number of overbank discharge days was reduced from 10 to less than 2 days. The extension of the floodplain inundation time observed along this reach since 1990 is independent of a gradual deepening of the channel, and is caused by the increasing frequency of large floods. Along the shallowing channel the duration of the floodplain flooding has been growing into long periods that are independent of long-term river discharge patterns. The inundation time near Pińczów had been growing until 1969 (reaching 80 days per year), after which it shrank to less than ten days and increased again during the last decade (to 30 days per year). The main cause of the increase in the flood risk near Pińczów (the largest town on the river) observed since the mid-1990s seems to be the continuing shallowing of the river channel, as a result of misguided training and drainage projects, and only partly due to the greater frequency of large flood events. The engineering measures have resulted in effective drainage of large marshy areas adjacent to the anastomosing reaches. The flood risks near Pińczów could be partly mitigated by a revitalisation of the drained wetlands and by returning their functions (Łajczak 2006b). In the mouth reach of the river, downstream from Wiślica, the Vistula backwater effect generates a very high flood risk level, manifested by the long duration of floodplain flooding (up to 100 days) and

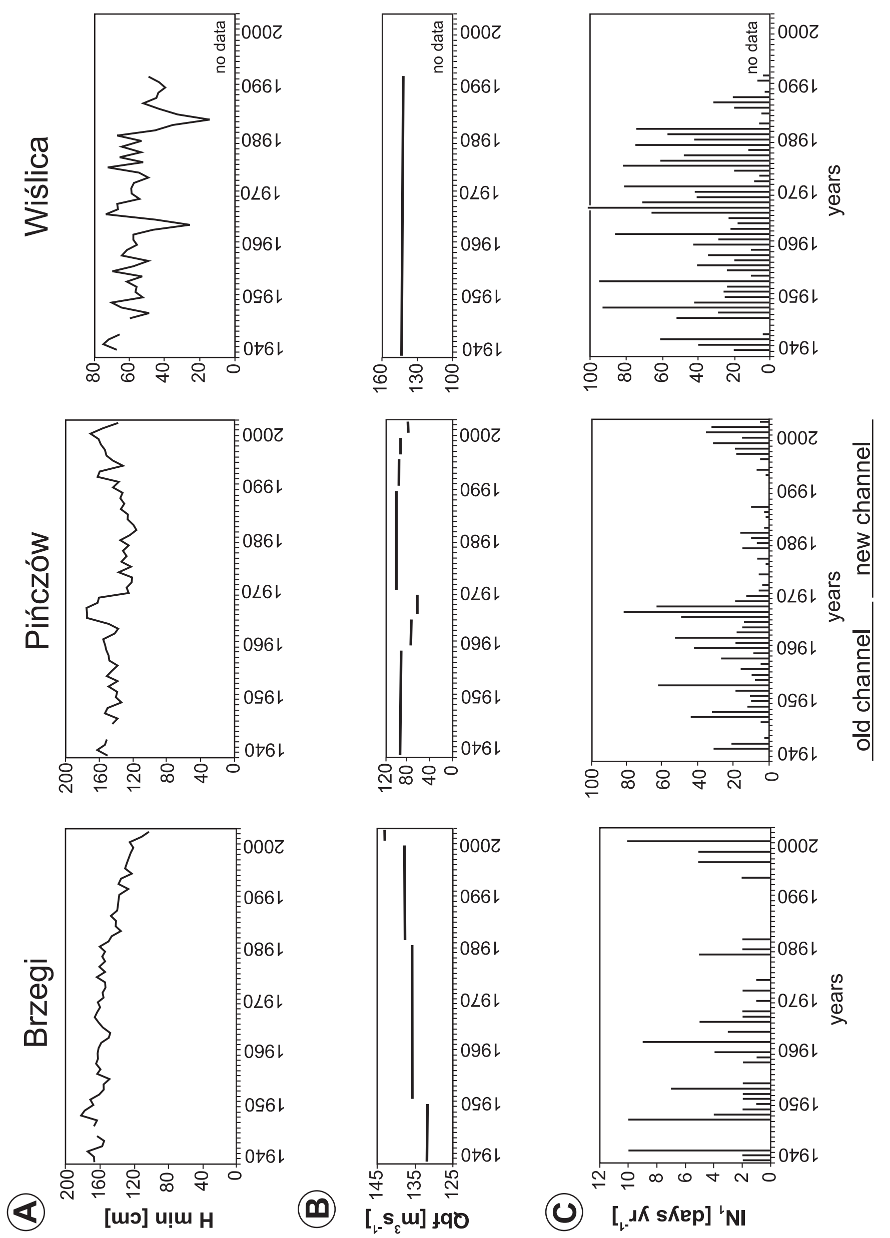

Figure 5. Minimum annual water levels Hmin during 1939–2003 (A) and change in the bankfull discharge Qbf (B), as well as the change of the overbank IN$_1$ water levels (C) at water gauge stations in Brzegi, Pińczów and Wiślica.

the highest water levels recorded along the entire river. The fluctuation in the Vistula water level in the area reaches up to nine metres, and the backwater effect can go up to Wiślica when large flood events are taking place on the main river. With its long retention of flood water, the Nida river has seen a mixture of flood risk improvement and deterioration, depending on the reach, as a result of river training. The only significant changes in the risk levels include the floodplain inundation duration and territorial extent. The river has no significant impact on flood risks in the Vistula valley.

Uniquely among major tributaries of the upper Vistula, the Nida has a valley already subject to several legal conservation statuses (including as a Landscape Park, an ecological corridor and a *Natura 2000* area), which only allows environmentally sound methods of flood risk mitigation (Łajczak 2006a, b). These methods might include revitalisation of the extensive wetlands, now mostly drained, and an expansion of the territory between the embankments to increase its volume. The earlier plans to erect a dam on the Nida upstream of Brzegi, and indeed any training measures that would introduce large quantities of sand, should be seen as undesirable.

THE FORELAND COURSE OF THE RIVER VISTULA

The foreland course of the River Vistula is the most thoroughly investigated part of the study area in terms of changes to the flood risk caused by river training. The engineering projects, involving an approximately 30% reduction in channel length, new stone spurs and bank protection, were designed to prepare the river for its role as the country's main waterway, and to protect adjacent areas from flooding. During the 20th century, modifications to the cross-section of the river channel included deepening by an average of two metres (and a maximum of 4 m) and large scale deposition in the bank zones. Local level differences in the channel cross-section increased three-fold compared to the early 20th century. Conversely, there were also cases of the channel becoming shallower, i.e. in the Oświęcimska Basin upstream of the Przemsza and Soła confluences and over a longer reach where the river breaks through the Polish Uplands. The alternating pattern of deepened channel sections and sections becoming shallower is therefore a characteristic feature of the foreland River Vistula during the river-training era (Fig. 6). Another characteristic of the channel morphology's impact on the discharge conditions is the continuing trend for the channel's width to average depth to decrease, as measured at water gauges (Łajczak 1995a). As a result of an increased speed of flow, caused by modifications to the cross- and longitudinal sections of the channel, the bankfull volumes continue to grow at various rates, as recorded by the gauges (Fig. 7). The bankfull volumes tend to differ ever more from the average medium-high discharge, to which they were similar prior to the first river training projects. During the 20th c., this increase in the bankfull discharge varied along the river course studied and reached three-fold, depending on the scale of the cross-section change.

The combined average duration of the flooding within the embanked floodplain and the number of flood events vary greatly along the stretch of river being investigated (Fig. 8). Both of these characteristics express an increase in flood risk , and display a relationship wih the scale of the post-river training cross-section evolution. They are highest in the reaches which have become shallower, and only slightly lower in the least deepening reaches. Conversely, the lowest values are observed along the most deepened channel reaches. As an example, the reach of the Vistula crossing the Polish Uplands gap has a frequency and combined duration of flood

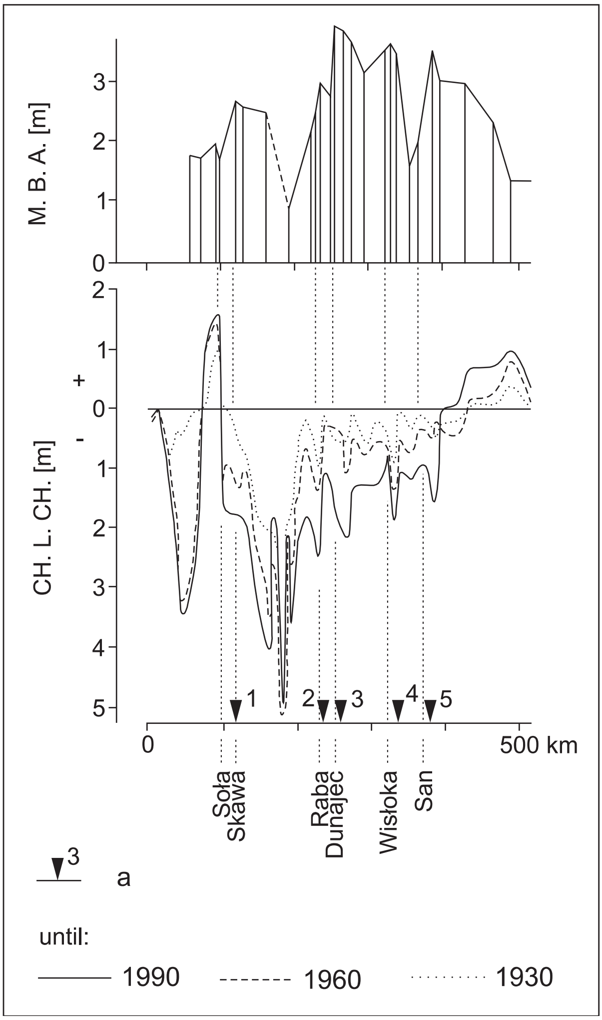

Figure 6. Change in channel depth following river training in the foreland River Vistula CH.L.CH. and average thickness of deposits in bank zones M.B.A.
a) selected water gauges (1—Smolice, 2—Jagodniki, 3—Karsy, 4—Koło, 5—Zawichost).
The confluences of the principal Carpathian tributaries are also indicated. Changes in the depth of channel until 1930, 1960 and 1990.

events up to 15 times greater than along the Cracow reach of the river.

Since at least 1930, the foreland Vistula has displayed a trend whereby the overbank water levels have been shrinking. Until 1990, this trend was unrelated to the long-term discharge fluctuations and was a result of channel deepening (Fig. 9). The trend is proportionally related to the deepening rate (Łajczak 1995a, 1999). However during the period 1931–1990, the duration of the over-bank water levels along the most deepened

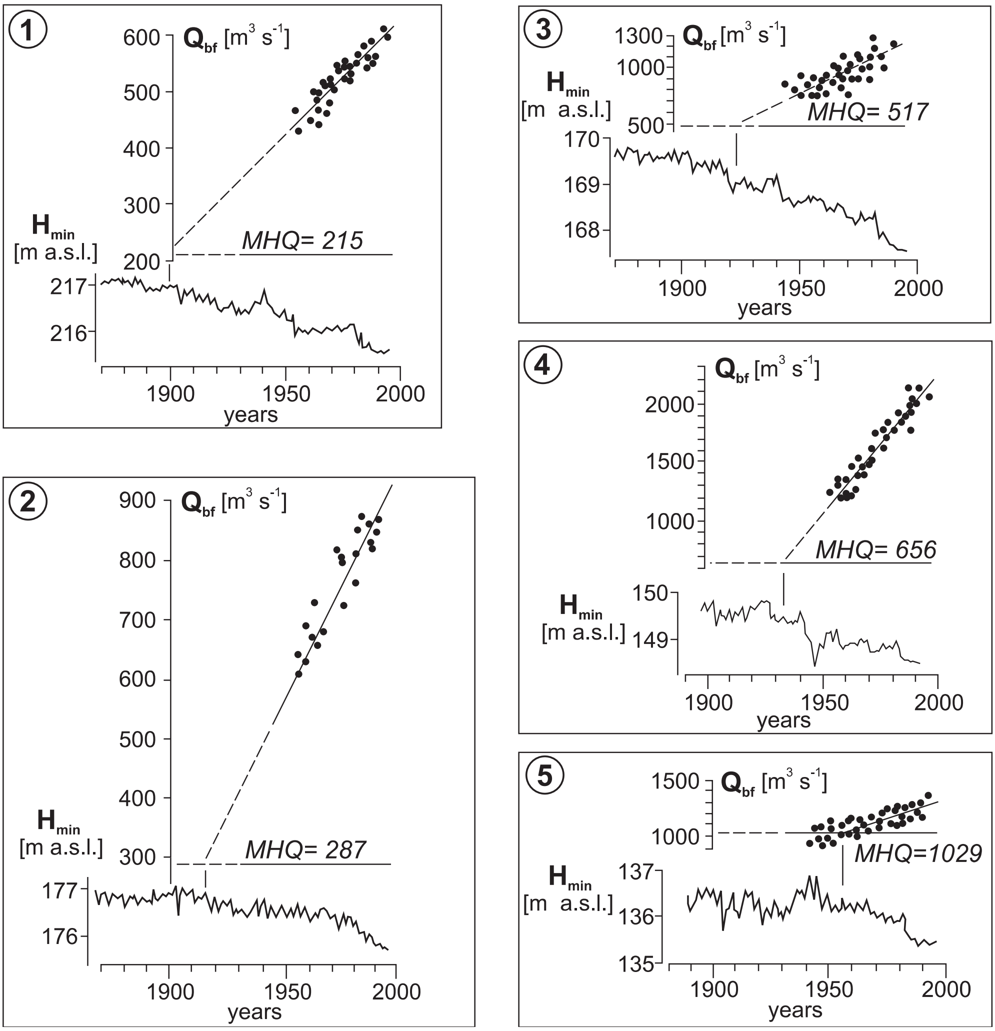

Figure 7. Change to bankfull discharge Qbf compared to medium high discharge MHQ against minimum annual water levels Hmin at selected water gauges on the foreland River Vistula. Water gauges are numbered as in Fig. 6.

reaches of the channel displayed only a weak decline, accompanied by generally low values of the IN_1 parameter, up to a maximum of approximately ten days per year. This may mean that the decline in this parameter along the most deepened reaches had already started before 1930. Lack of data prevents a similar analysis of the overbank water level duration after 1990, when a number of large flood events occurred. During the period 1931–1990, overbank discharge along the most deepened Vistula channels occurred on average every second year, but prolonged periods of up to ten years without such periods were also recorded. Further downstream, along less deepened reaches of

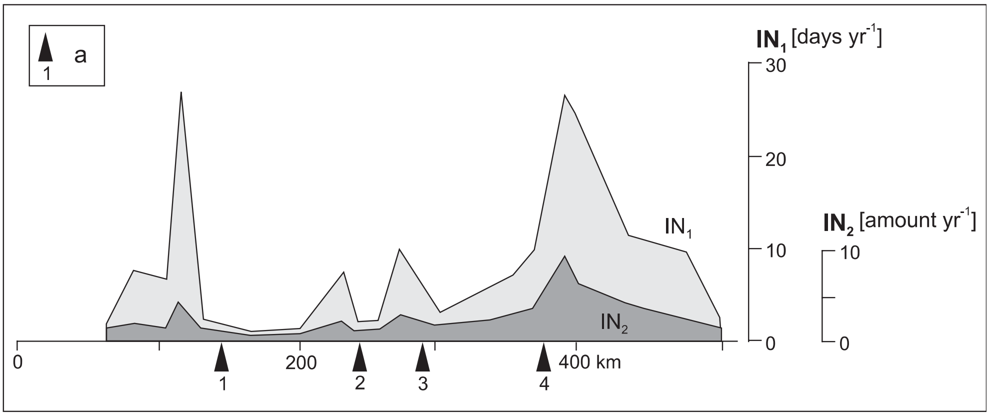

Figure 8. Differentiation of duration of overbank IN_1 water levels and number of flood events with such water levels per year IN_2, along the foreland course of the River Vistula. a) selected water gauges (1—Smolice,2—Jagodniki, 3—Szczucin, 4—Zawichost).

the river, the decline in the duration of flooding on the floodplain was more marked. Downstream from the Dunajec confluence the IN_1 parameter dropped from approximately 10–20 days per year during the years 1931–1960 to less than ten days before 1990. Over the period 1931–1990, this section of the river experienced overbank water levels nearly every year, which may mean that the duration of the flooding of the embanked space is shortened more effectively during the initial period of channel deepening following river training than at an advanced stage of change in the geometry of a trained channel. Downstream of the River San confluence, the Vistula channel is not subject to intensive deepening, and there are places where it may even be becoming shallower. Overbank water levels were recorded every year of the study period—peaking at 50–70 days per annum during the 1931–mid 1960s period. Afterwards, the number of days with overbank water levels declined again to a maximum of 30 days annually in the 1980s.

The lack of a clear-cut trend involving a reduction in the number of days with overbank water levels along the foreland course of the Vistula from 1931 to 1990 might suggest that such a trend may have prevailed earlier on, i.e. in the late 19th century and during the first three decades of the 20th century, when the pace of channel deepening was already advanced, such as near Cracow. Downstream, where the deepening process only started after the 1930s, the trend towards a rapid decline in the periods of floodplain flooding between the embankments was only noted after 1930. Below the confluence of the River San the trend to a decline in the number of days with overbank water levels is not very advanced, and started only in the 1970–1980s because the river training efforts along this stretch of the river starting later than elsewhere.

Another result of the engineering projects in the foreland course of the Vistula is the restriction of flooding of the embanked floodplain along the considerably deepened channel (> 2 m) to just the summer season. Where the deepening is only minor (< 1 m), or the channel is becoming shallower, this part of the floodplain may also be flooded during rapid thaws. Prior to river training, the entire course of the river floodplain experienced flooding during both rapid thaw floods and summer floods. The foreland-course engineering projects effectively eliminated the early-springtime flood risk along the most modified reaches alone. During summertime, floods have only become shorter as a result of the training measures, except along the upland gap reach.

and Zawichost, and by a half between Smolice (the confluence of the River Skawa) and Sierosławice (the confluence of the River Raba), the latter being the most deepened channel section. The accelerated movement of the flood waves along the deepened reaches of the foreland Vistula is considerably influenced by the greater concentration of similarly-induced flood waves on the

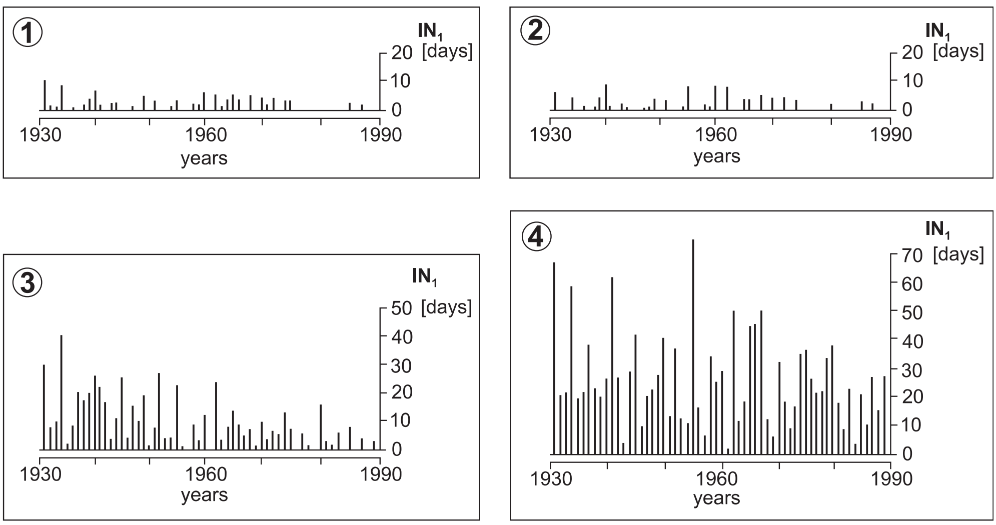

Figure 9. Change of duration of overbank water levels IN_1 at selected water gauges on the foreland course of the River Vistula during 1931–1990. Water gauges numbered as in Fig. 8.

Another effect of the training of the Vistula foreland is an increased concentration of flood waves, as a result of the accelerated flow observed across the entire spectrum of water levels (Punzet 1991; Łajczak 1995a). According to Punzet, during the 20th c., the Cracow reach displayed a trend to a shortened duration and increased height of the flood wave, as well as to an increase in the frequency of extraordinary flood peaks. A combined effect of these changes has been to cause the flood wave travel time to shorten along the foreland course of the river, including by one-third between Goczałkowice

lower courses of the Carpathian tributaries (Punzet 1991; Wyżga 1993). The post-river training development of the foreland Vistula channel has produced a trend for the volume of the flood waves to be reduced as a result of their greater concentration and higher peaks (Punzet 1991). This could be partly explained by the effect that the bankfull discharge has been growing at the expense of the overbank discharge following the advent of the river training projects, an effect previously overlooked. The trend for a declining duration of the overbank water level periods, initiated at various dates in the 20th c., has been observed along the considerably deepened reaches, and is independent of the long-term fluctuations of the Vistula discharge (Łajczak 1995a).

The erection of flood embankments has reduced the flooding zone up to 50-fold along the foreland course. Events whereby the water tops the new embankments and spills over are very rare, and limited to days with extreme water levels. Combined with the causes mentioned above, this dramatic reduction of the flooding zone has led to increased water level amplitudes along the course of the Vistula we are examining, especially after 1920 (Osuch 1991; Punzet 1991). They are currently double the value recorded before the embankments, and may reach nine metres (Soja and Mrozek 1990).

Just as in the tributaries, assessment of the foreland course of the Vistula in terms of the impact of river training on flood risk is complex. Taking into account the duration of the overbank stages and the extent of the flooding zone, the duration and area aspects of the flood risk were reduced during the 20th century. This is a result of faster flood wave travel, and of the fact that minor summertime floods and all the thaw floods remain within the bankfull stage. The number of days with overbank discharge was reduced, with the exception of reaches without any significant deepening effect or with a shallowing trend. Just as in the Carpathian rivers, the increased flood wave speed may, , be regarded as an additional risk factor in certain circumstances. The third feature of flood risk, i.e. the height of peak river water levels, demonstrates a growing flood risk along the entire channel, within the embankments only, during the 20th century. Only extremely high water level events threaten to spill over and undermine the embankments, which then need maintenance. This is a result of:

- a trend for peak river water levels during subsequent large flood events to increase, and for their durations to shorten;
- a trend towards an increasing frequency of exceptional flood peaks;
- an increasing speed of large flood waves.

DISCUSSION AND CONCLUSIONS

As demonstrated by reference to the example of the trained foreland course of the Vistula, the alternating pattern of reaches featuring varying degrees of cross-section modification translates into hydrological effects, especially with regard to flood risk. This situation is typical for the entire course of the river (Łajczak 1995a). The reach downstream of the River San confluence, where the deposition is at its most intensive, stands out as having the greatest flood risk along the river (Jędrysik and Rusak 1982). This should be seen as a consequence of the shallowing and broadening processes, along the entire channel length, that began at least as far back as in the 17th century, driven by the deforestation of the drainage basin. Only since the 20th century should this be seen as a consequence of the river-training triggered development of the upstream reach (above the River San confluence). Along the entire foreland Vistula, as well as in the lower courses of the Carpathian tributaries and in the upland and lowland tributaries, the current flood risk is critically determined by the effects of river training measures. I would therefore confirm Punzet's conclusion (1991) that river training as broadly understood, along the course of the Upper River Vistula has a large impact on the process of flood wave formation in the river.

The anthropogenic aspects to the current evolution of flood risks in the foreland course of the Vistula and in the middle and lower courses of its tributaries involve an overlap effect of two contradictory trends: (a) the falling risk level in view of the shortening of floodplain inundation time and territory, and (b) the growing risk from the increasing height of the flood water. These two trends are typical over most of the river course where its channel has been deepened. The former of the two trends (a) seems to be more significant for this analysis of flood risks. Indeed the benefit of the shortening of the inundation time over the unembanked area or the undeveloped embanked floodplain is greater than the losses incurred, because of the rare cases of flooding of inhabited and agriculturally used areas, as a result of breaches in the adequately high levees. This can be illustrated by the foreland course of the Vistula between the confluences of the Dunajec and Wisłoka rivers, where—after the erection of up to six-metre-high embankments—the floodplain inundation time was reduced 10-fold and the area 20-fold during the period 1930–1990. The coinciding increase in the water level amplitude to nine metres was a result of the simultaneous channel deepening and maximum floodwave level increase (Punzet 1981, 1991; Jędrysik and Rusak 1982; Soja and Mrozek 1990; Hennig 1991; Osuch 1991; Łajczak 1995a, 2006a). The areas beyond the levees remain unprotected from exceptionally high floodwaves, despite the vertical extension of the embankments after the great floods, and other maintenance measures.

The greatest flood risk levels along the river course analysed, in all three respects, were recorded in the valley sections coinciding with the channel reaches that displayed a shallowing process, lower gradients and only partial or no embankments. This type of valley section is typically found at the end of long stretches where the channel has been significantly shortened, narrowed and deepened (its slope gradient additionally increased) as a result of training measures, which normally included long uninterrupted embankments on both sides of a narrow floodplain. An illustration of this pattern is found using certain water gauges on the Rivers Nida and Vistula. On the Nida near Pińczów, the inundation times were extended more than fourfold during the period 1939–1969. In 1970, the construction of an artificial channel reduced that time to just a few days per year, but a backlash reaction returned it to ten times more. While at Pińczów the embankments reduce the flooded area to a very narrow strip, just two kilometres downstream from the town they disappear for the rest of the river course all the way to its confluence with the Vistula, exposing a floodplain up to three kilometres wide. The historically unprecedented extreme flood wave recorded during the 1997 summer flood not only topped the embankments along many reaches, but remained high throughout the lower course of the river, causing a high degree of damage. Along its partly embanked upland gap reach, the Vistula has a broad floodplain of up to one kilometre. Unlike its long upstream reach, this section of the river displayed no reduction of flooding time, but a slow opposite trend after 1930. The numbers of days with flood effects varied across a broad range of 10–70. The currently higher flood risks observed along this reach are also partly a result of the heightened culminating floodwaves developing in the upstream reach with its deepening channel (Łajczak 1995a,b, 2006a,b).

When looking at various flood risk mitigation options in the foreland course of the Vistula and the middle and lower courses of its tributaries it must by assumed that the current channel development trends, initiated or accelerated by the training projects, will continue in the long term (Łajczak 1995a, 1999). These options tend to be much more limited in the valley sections with shallowing channels than those with deepened channels. In the former case the risk could be mitigated by halting the channel deepening process, or by even less realistic measures, such as a broadening of the distance between the embankments or an increase in their height. In the latter case, featuring long reaches of deepened channels with fast-moving flood waves travelling along a narrow floodplain between the embankments, the risk could only be mitigated by heightening the embankments. Where the deepened channel reach is relatively short there is an option of setting aside large polders beyond the embankments, such as between the confluences of the rivers Soła and Skawinka along the Vistula valley (Nachlik and Wit 1997; Nachlik 1998; Wit 1999). The role of a polder can also be played by the often inundated floodplain along a shallowing river channel, such as along the lower Nida. Halting a channel deepening process that provides sandy material for a downstream shallowing reach is feasible on a small scale, such as along an anastomosing reach of the middle-course River Nida. In this case it would require a parallel reinstatement of the nearby former wetlands, which could play the role of an effective deposit accumulation zone (Łajczak 2006b).

Measures to mitigate the flood risk must also take into account the valley's conservation status. Where no legal conservation is involved, such as in the Carpathian rivers or along the foreland course of the Vistula, a more active floodwave management can be achieved by controlling discharge from artificial lakes. Ideally, this could produce a flattened floodwave extended in time (Punzet 1959, 1973, 1991). In the River Nida valley, subject to several conservation statuses, only environmentally sound methods are feasible, such as reinstatement of the natural qualities of the anastomosing reaches and the adjacent wetlands, or expanding the territory between the embankments.

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